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Engine Technology Challenges for a 21st Century High-Speed Civil Transport

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Abstract

Ongoing NASA-funded studies by Boeing, McDonnell-Douglas, General Electric, and Pratt & Whitney indicate that an opportunity exists for a 21st Century High-Speed Civil Transport (HSCT) to become a major part of the international air transportation system. However, before industry will consider an HSCT product launch and an investment estimated to be over $15 billion for design and certification, major technology advances must be made. This paper will give an overview of the propulsion-specific technology advances that must be in hand before an HSCT product launch could be considered.

Introduction

Ongoing NASA-funded studies[1,2] continue to indicate that an opportunity exists for a second-generation supersonic transport to become a key part of the 21st century international air transportation system. In spite of the recent worldwide economic downturn and the resultant impact on the world's airlines, long-distance air travel is projected to increase approximately 5 to 6 percent per year over the next two decades.[3,4,5] This growth rate suggests that by the year 2015 more than 600 000 passengers per day will be traveling long distances, predominantly over water. These routes would be among the most desirable for an HSCT as part of an international air transportation system. Beyond the year 2000, this portion of the air transportation market is estimated to be the fastest growing segment.

The potential market for an HSCT as a fraction of the projected wide-body aircraft demand is shown in Fig. 1. The figure indicates that the projected HSCT fleet size is very sensitive to the level of technology available. The economic viability of any airplane is a balance between the aircraft cost and the commercial value. The technologies employed in the aircraft design must improve the product performance but not at the expense of excessive increases in operating expense and maintenance cost.

Simply stated, the HSCT will be a technology-driven airplane. Without significant advances in the airframe and propulsion technologies over the levels currently available, there will be no second-generation supersonic transport! In order for an HSCT to become a reality, the technologies developed must contribute to an aircraft design that is (1) environmentally compatible and (2) economically viable.

Environmental Barrier Issues

Ozone Depletion

As related to propulsion, the environmental barrier issues that must be dealt with are ozone depletion and airport noise (Fig. 2). These environmental problems must be solved before additional HSCT-related research is warranted. Phase I of NASA's High-Speed Research Program (HSR) is aimed at developing the technologies associated with environmental compatibility, and a proposed follow-on phase II program is aimed at developing the technologies associated with economic viability.

Depletion of the Earth's ozone layer is attributed to the HSCT engine exhaust products, specifically the nitric oxide (NO_x) levels. Thus, combustor designs must evolve so as to produce ultralow levels of NO_x while at the same time not compromise combustion efficiency and operability across the mission profile. The NO_x level goal for the combustor technology element of HSR originated largely from the ongoing atmospheric impact assessments made with state-of-the-art two- and three-dimensional atmospheric modeling codes. These impact studies are being performed by some of the world's

leading atmospheric scientists as part of the HSR program. Figure 3 summarizes the most recent set of results obtained from a collection of different two-dimensional models. Calculations were done for varying levels of combustor emissions (expressed in terms of emission index EI in grams of NO_x produced per kilogram of fuel burned) for flight Mach numbers between 1.6 and 3.2. The results indicate that less than a 1-percent steady-state ozone depletion level is predicted for Mach numbers between 1.6 and 2.4 for emissions indices of 15 or less. However, because of uncertainties in model predictions, NASA has established an emissions goal for an HSR of 5 gm NO_x/kg of fuel burned. These results are encouraging in that the models include the latest understanding of the heterogeneous chemistry effects of the upper atmosphere which have been recently discovered in NASA's Upper Atmospheric Research Program. Such low predicted levels of ozone depletion are felt by most scientists to present little or no danger to the Earth's population.

The goal of the combustor element of HSR is to evolve and demonstrate the combustor technologies that would contribute to a combustor design with an EI level of no greater than 5 gm NO_x/kg of fuel at supersonic cruise operating conditions. In addition, an international consensus regarding the acceptable level of HSCT emissions must be attained. Such a consensus must include the engineering, scientific, and environmental sectors, and it must result in the establishment of an emissions certification rule acceptable to the international community before large industrial expenditures can be appropriated for development.

The magnitude of the HSCT emissions challenge is depicted in Fig. 4. For the range of HSCT engine cycle temperatures and pressures of interest (shown in terms of a NO_x severity parameter which is a function of combustor temperature and pressure levels), the technology of current subsonic engines would result in unacceptable NO_x levels of about 40. Using state-of-the-art technologies would reduce the NO_x levels somewhat but nowhere near the program goal of 5 gm NO_x/kg of fuel. Clearly, major technology advancements must be made if an ultralow NO_x combustor design is to be realized.

The NO_x reduction strategies being investigated in HSR are presented in Fig. 5. The key to achieving ultralow levels of NO_x is to have uniform burning that occurs sufficiently away from stoichiometric conditions. The two combustor concepts being investigated are the (1) rich burn-quick quench-lean burn (RQL) and (2) lean-premixed-prevaporized (LPP). The RQL is a two-stage concept whereas the LPP features combustion only on the lean side of the curve. Because each concept has strengths and weaknesses, we believe that both should be evaluated in a multiphase research program through tests conducted in flame tube rigs (such as that shown in Fig. 6 at the NASA Research Center). Such tests permit an orderly scientific evaluation of the ultralow NO_x potential of the concept as well as the development of a parametric design data base. Currently, flame tube tests are underway at NASA Lewis, General Electric (GE), and Pratt & Whitney (P&W), and early results indicate that both the RQL and LPP concepts are capable of producing NO_x levels that at least meet the program goal of no greater than 5 gm NO_x/kg fuel burned.

The next step in the combustor technology evolution is to conduct sector tests incorporating the design information gathered from the flame tube tests. These sector tests (typically about one-fifth of a full annular design) are more representative of a real annular combustor and thus provide an increased level of confidence that the NO_x emissions goals can be met. Sector tests at both GE and P&W are scheduled to begin this year and be completed by the end of the 1995 fiscal year. Good results from the sector tests will provide the basis for the design, fabrication, and testing of large-scale, full annular combustor designs to demonstrate low-NO_x level performance at cruise conditions and acceptable operability across the entire mission profile.

Computational fluid dynamics analysis codes have a key role in the HSR program. They allow a preliminary screening of concepts and approaches prior to testing. In particular, codes that accurately model reacting flow fields serve as a diagnostic tool to interpret experimental data and to design low-NO_x combustors. For example, Fig. 7 shows the predicted temperature contours for the RQL combustion concept in the NASA Lewis flame tube rig (shown in Fig. 6).

Airport Noise

The other HSCT environmental barrier issue is aircraft noise during the takeoff and landing. The prime contributor to an HSCT noise signature is the jet exhaust, and thus an approach to quieting the jet exhaust without seriously impacting nozzle aerodynamic performance, size, or weight must be developed. The amount of nozzle noise reduction required is directly related to the nozzle exhaust velocity which in turn is related to the engine cycle characteristics. Figure 8 shows the sideline noise reduction levels required as a function of engine cycle type. The reduction levels required vary from over 20 dB for a turbojet cycle to only 1 to 2 dB for a high-flow engine concept. Note that the sideline noise reduction levels shown are those projected to be required to meet the current noise regulations for subsonic transports (FAA FAR 36 stage III). The increasing worldwide concern for the environment suggests that a stricter noise rule may be in place by the time the

HSCT would be expected to enter the transportation system. Thus, it is important to look at engine cycles and nozzle concepts that have potential for noise levels below those currently required for certification.

The first step in designing a nozzle that will contribute to an environmentally compatible HSCT is to conduct subscale model tests to evaluate the low-speed aeroacoustic performance of nozzle concepts for engine cycles of interest. The nozzle tests are being conducted in wind tunnels and free-jet facilities (Fig. 9) of NASA and industry. Although acoustic suppression characteristics are the focus of the initial tests, aerodynamic performance should not be sacrificed for nozzle noise reduction. Currently, we think that the ratio of noise reduction (decibels) to thrust loss (gross thrust coefficient) must be on the order of 4:1. Overall, the initial HSR nozzle tests results are most encouraging in that some of the first-generation configurations have met or exceeded noise reduction levels required for stage III aircraft. Fundamental jet mixing studies are currently providing insights into the governing physics of the nozzle flow fields, and the results are being used to design improved second-generation nozzles.

Rapidly maturing computational fluid dynamic prediction tools are also impacting the HSR nozzle research (Fig. 10) in much the same way they did the combustor research previously discussed; viscous analyses provide concept screening as well as flow field diagnostics. These analytical tools will be used to design future-generation nozzles that further improve aeroacoustic results and refine aerodynamic contours to achieve the required levels of thrust coefficient performance.

It must be pointed out that the solution to the HSCT noise barrier issue requires a systems engineering approach such as that presented in Fig. 11. Contributions to vehicle noise reduction will come from several sources: advanced exhaust nozzles and engine cycle characteristics; advanced high-lift concepts being pursued as part of HSR; and possibly advanced aircraft operational procedures such as programmed lapse rate. System trade studies are being performed to identify the best combination of noise reduction technologies.

Advanced, high-temperature engine materials will contribute to the HSCT environmental compatibility and economic viability. Figure 12 shows the candidate engine materials forecast for use in a propulsion system for an EIS 2005-2010 HSCT. A systems studies assessment of the impact of these materials indicates that a 24-percent reduction in aircraft takeoff gross weight (TOGW) and a 4-percent reduction in thrust specific fuel consumption would be gained by using these advanced materials.

The materials of choice in HSR are ceramic matrix composites (CMC) for the combustor liner and intermetallic/metal matrix composites (IMC/MMC) for the nozzle. Conventional film cooling techniques cannot be used to cool the HSCT combustor walls: in particular, for the RQL combustor, local hot spots and unacceptably large production rates of NO_x would result. Thus, a CMC must be developed for use in the design of a combustor liner which incorporates backside cooling. The exhaust nozzle of a supersonic cruise propulsion system is large and can weigh approximately the same as the core engine (Fig. 12). Conventional materials used in the design of candidate nozzle configurations would require as much as 10 percent engine cooling air to keep the flow path subcomponents at acceptable temperature levels. The forecast properties of the IMC's under development in HSR would result in nozzle weight decreases of as much as one-third and would require no engine cooling air.

Three other enabling materials identified for a high-speed civil transport propulsion system are also being developed in HSR. Specifically, under development are lightweight materials for fan containment as well as more desirable materials for long-life compressor and turbine disks and turbine blade systems.

The other new materials projected for use in the HSCT propulsion system are not being developed in HSR because they are under development in such programs as the DOD/NASA Integrated High Performance Turbine Engine Program (IHPTET).

Economic Viability Issues

The propulsion technology efforts required to address the economic viability issues are presented in Fig. 13. The aerodynamic and acoustic performance of the critical propulsion components must be demonstrated through isolated, large-scale component tests. These components need not be full scale but must be large enough to include design intricacies such as movable surfaces, actuators, and seals. These components should also use the appropriate advanced materials in their designs. The successful completion of these component tests will confirm the design methodologies. System integration tests will be required to demonstrate the ability to integrate the closely coupled components and not sacrifice the performance levels demonstrated through the isolated component tests. Inherent in these system tests is the development of the relevant propulsion control technologies. An HSCT propulsion system will have a large number of control variables to ensure that the system performance be acceptably high across the speed range.

Currently, we feel that two systems tests must be performed to demonstrate a system technology readiness. A low-speed test at takeoff and landing conditions will show that the aeroacoustic performance is acceptable. This test, conducted with a wing simulation, will ensure a realistic representation of propulsion-airframe integration effects. The test must be carried out in an acoustic wind tunnel such as the National Full Scale Aerodynamic Complex (NFAC) at the NASA Ames Research Center. The high-speed test should be done at supersonic cruise operating conditions, should emphasize the inlet-engine compatibility effects, and should especially demonstrate the ability of the inlet to resist external and internal disturbances without unstarting. Currently, the supersonic wind tunnels at NASA Lewis (10- by 10-ft) and AEDC (16S) are considered the prime facilities for such a test.

The large-scale, isolated component tests and follow-on propulsion system integration tests form the basis of the propulsion element activities portion of a proposed HSR phase II program which could begin as early as fiscal year 1994. This program has been planned by NASA with significant input from industry. The components chosen for scaleup and testing include the inlet, fan, combustor, and nozzle. The efforts would include the scaleup of the CMC and IMC/MMC materials developed in HSR I to produce combustor liners and nozzle subcomponents. These material efforts would demonstrate technology readiness to proceed with HSCT engine designs incorporating advanced high-temperature composites.

Figure 14 illustrates how the propulsion technologies impact the viability of an HSCT as expressed in the increase in aircraft takeoff gross weight (TOGW) resulting from individual technology shortfalls. These sensitivity coefficients come from the ongoing NASA/industry HSCT systems studies and reveal several important points. The major impact of shortfalls of the inlet and nozzle cruise performance indicates the need to take the component testing to large-scale realistic configurations. Similarly, shortfalls in the nozzle acoustic suppression can significantly increase TOGW. This sensitivity suggests the importance of conducting both ground and flight tests of the nozzle design to verify nozzle acoustic suppression capabilities before committing to a product launch. The impact of turbomachinery performance is also potentially large. However, these component technology needs are being addressed through other programs such as the DOD/NASA IHPTET program. The IHPTET program carries the technology development through engine ground tests.

Figure 15 presents a possible scenario for NASA- and industry-related efforts which could lead to the certification of an HSCT in the time period 2005 to 2010. The HSR I program which began in 1990 is aimed at technologies required for environmental compatibility. Excellent progress has been made already in developing ultra-low-NO_x combustor and low-noise nozzle concepts, which will be refined during HSR I. The proposed HSR II program would take these critical propulsion concepts and extend them to large-scale components to demonstrate technology readiness. Concurrent with the NASA-funded HSR program, industry is engaged in parallel complimentary research and development. As the HSR program technologies evolve and mature, the financial risk to industry will be reduced, and it will be willing to invest more resources. Thus, a product launch decision may be made as early as the year 2001.

Currently, industry and NASA are investigating the flight research requirements for a comprehensive HSCT technology development program. Two major propulsion-oriented programs being discussed are low-speed flight tests of the exhaust nozzle to demonstrate the noise reduction technologies and supersonic cruise flight tests of the inlet to demonstrate the approach to prevent inlet unstart. Additional work is required before the flight research needs are made final.

Concluding Remarks

This paper presented an overview of studies conducted by NASA and industry to develop the propulsion technologies required for a second-generation supersonic transport to become a reality in the 21st century. To date, excellent progress has been made toward solving the environmental problems resulting from supersonic flight. The next step is to develop economic viability-oriented technology.

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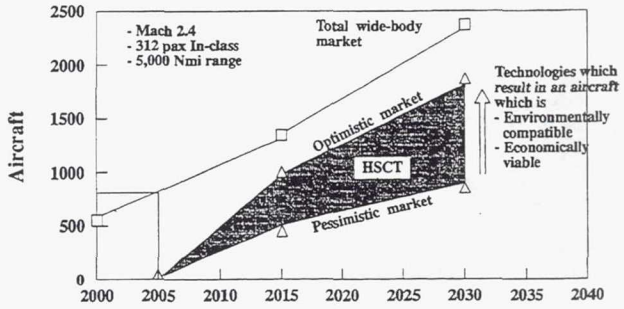

Figure 1.—The potential market for a high-speed civil transport.

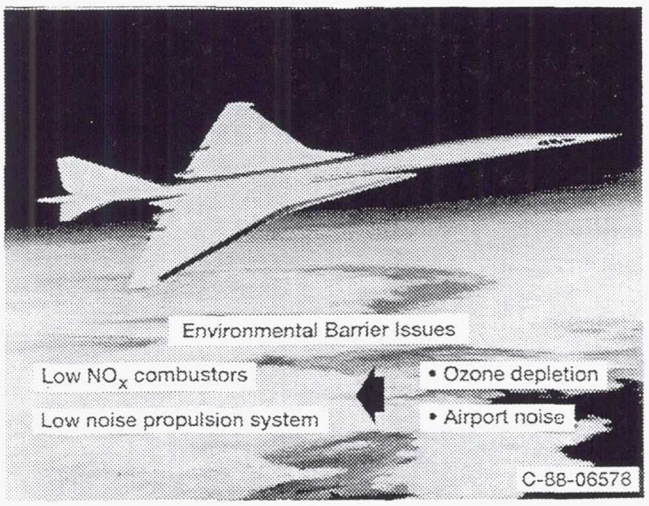

Figure 2.—Environmental barrier issues propulsion perspective.

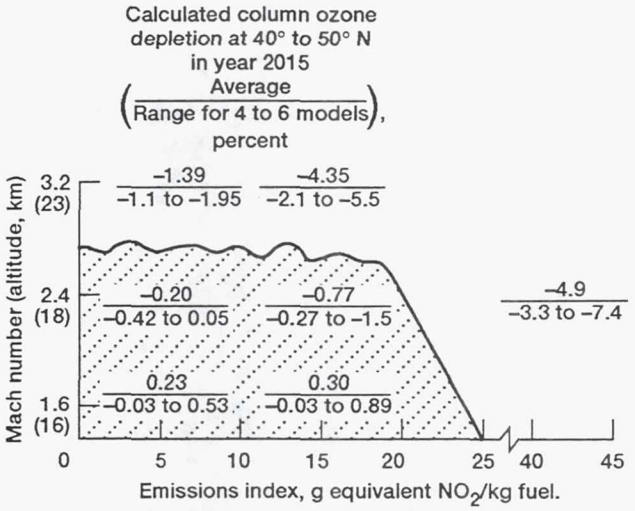

Figure 3.—Current atmospheric assessment. Heterogeneous chemistry assumptions: 70 Billion kg fuel/yr (~ 600-HSCT fleet).

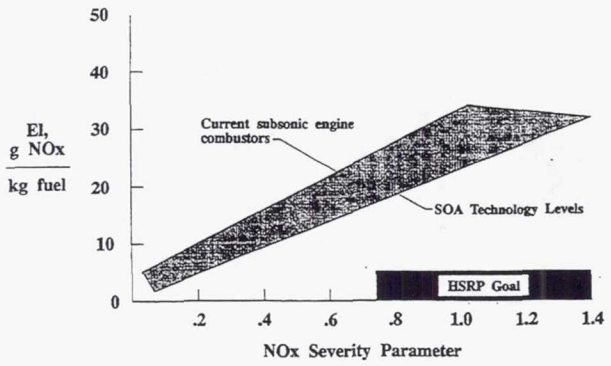

Figure 4.—NO_x emissions challenge for the high-speed civil transport.

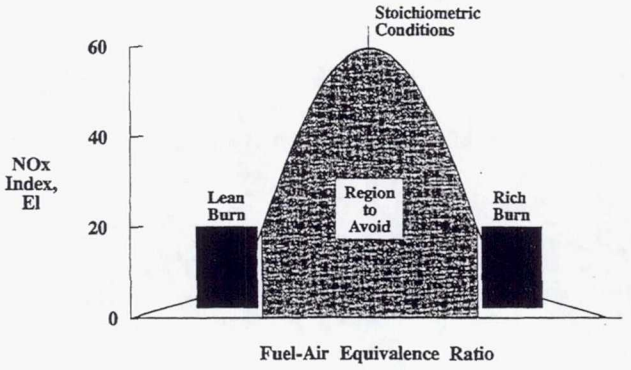

Figure 5.—NO_x control strategies.

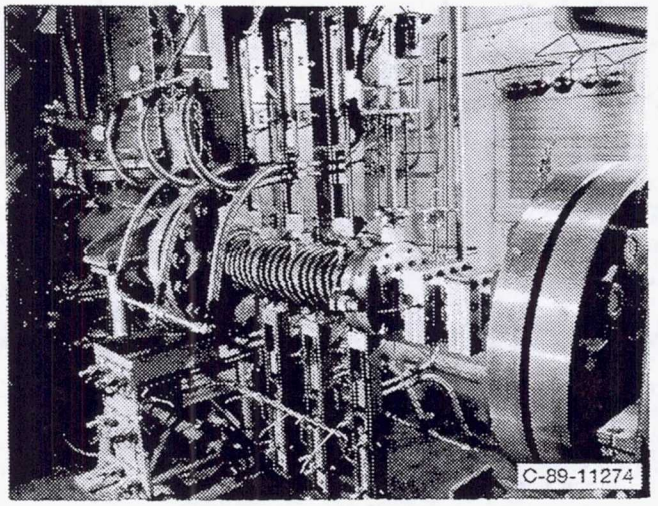

Figure 6.—Flame tube investigations: the first step.

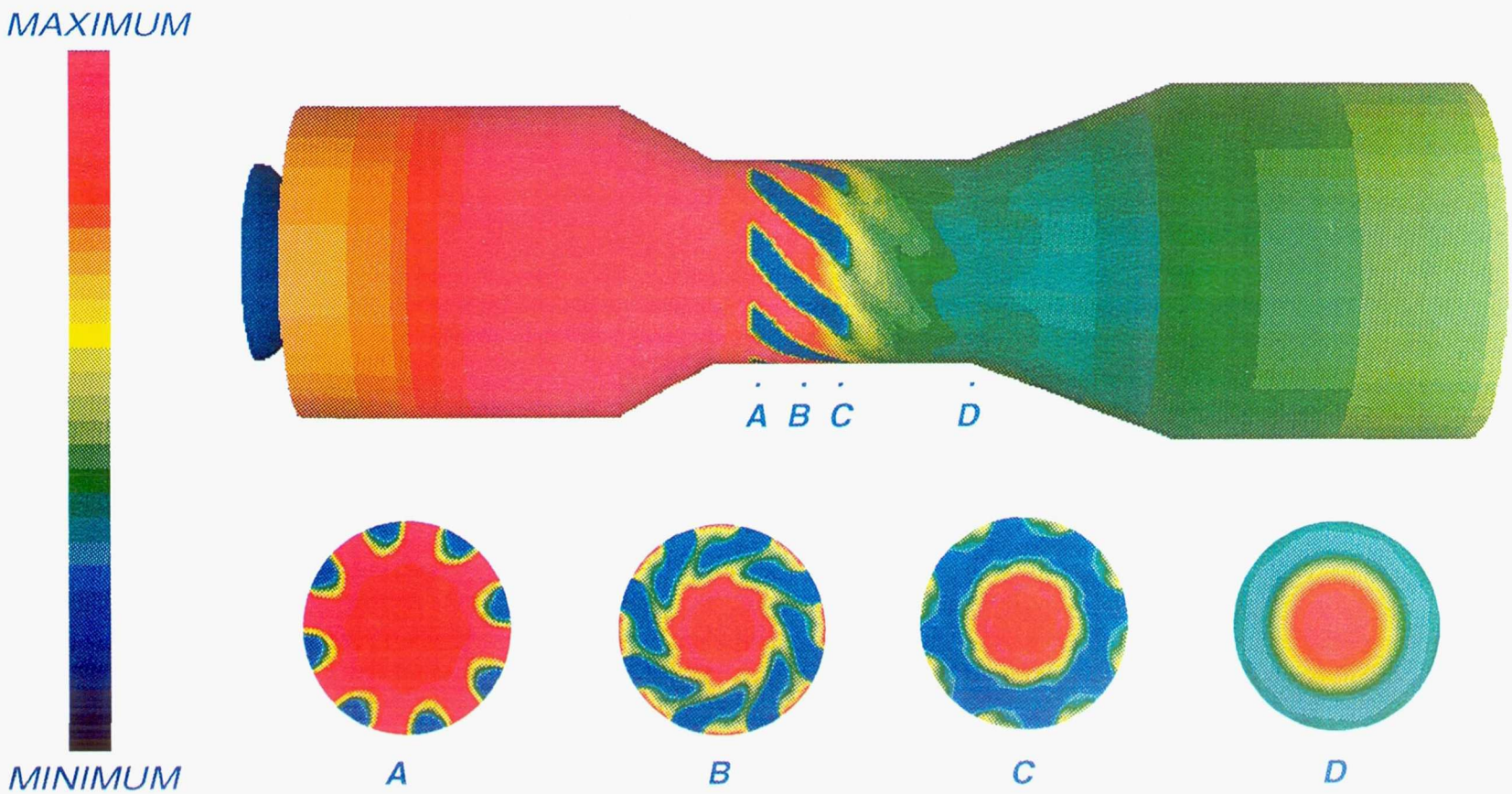

Figure 7.—Reacting flow analysis of HSCT combusion concepts.

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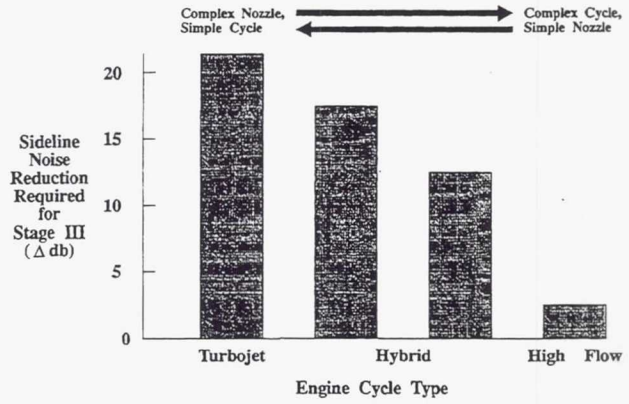

Figure 8.—HSCT propulsion system noise reduction challenge.

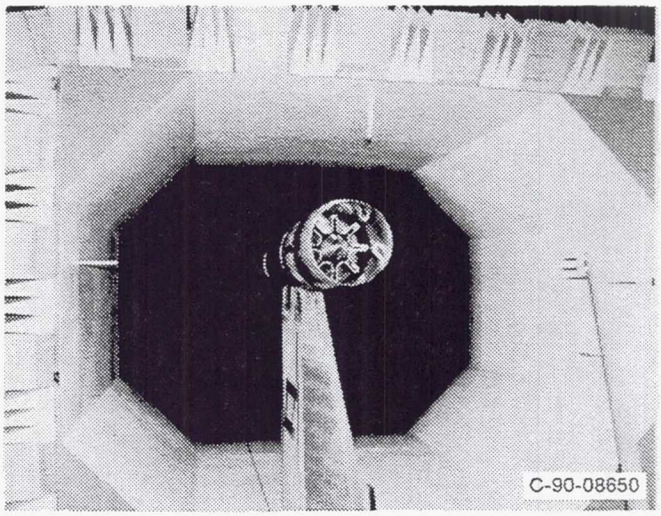

Figure 9.—Aeroacoustic tests of nozzle concepts: the first step.

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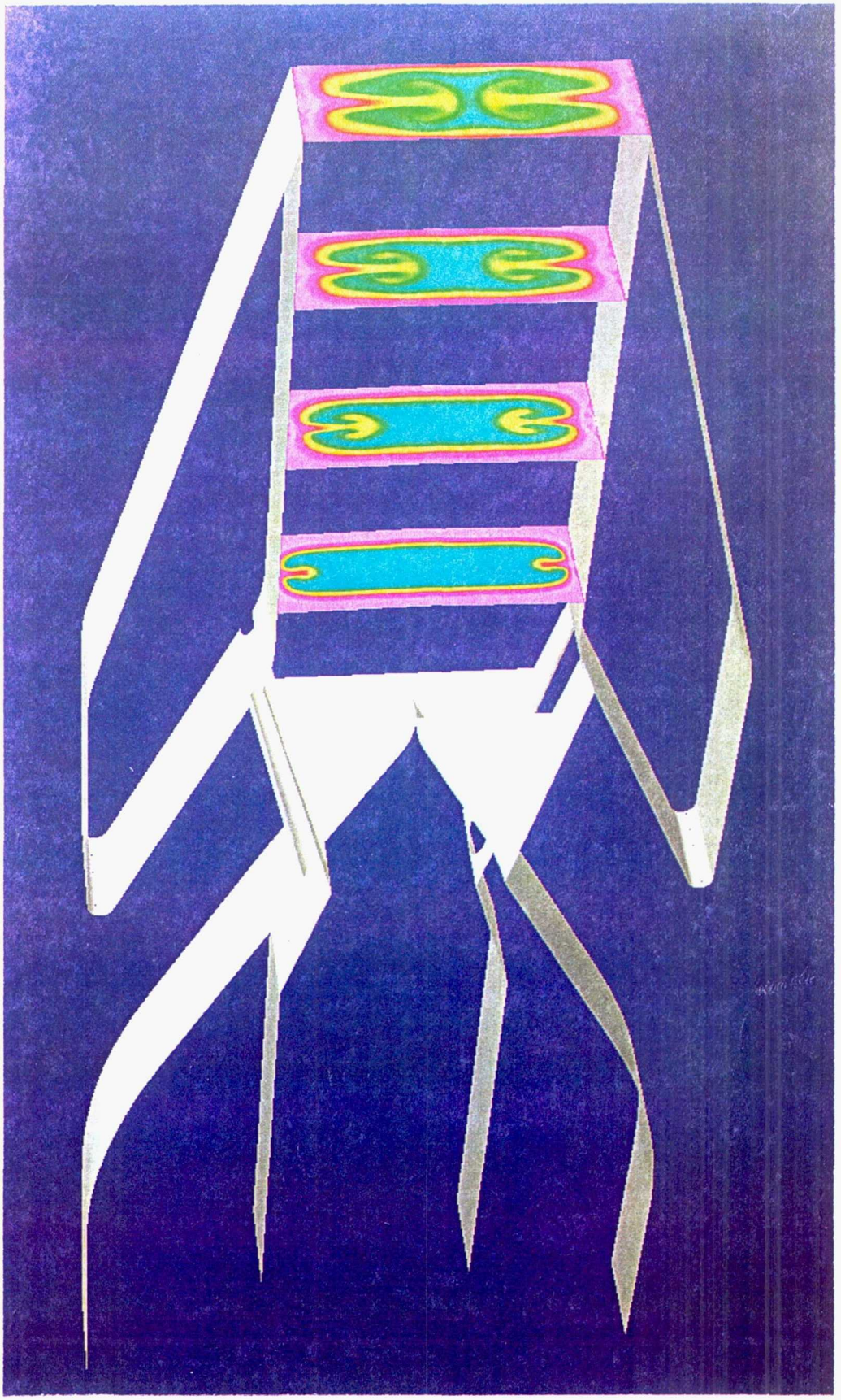

Figure 10.—Computational fluid dynamic predictions of nozzle flow field.

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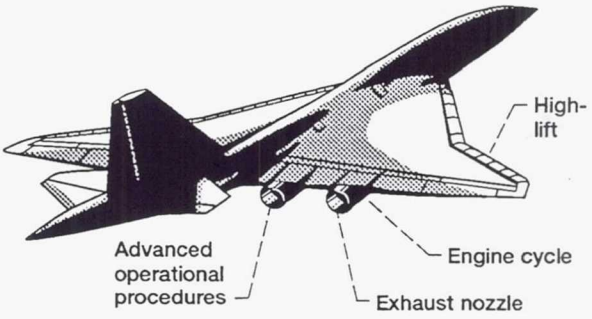

Figure 11.—The solution to the HSCT noise problem — a system integration approach.

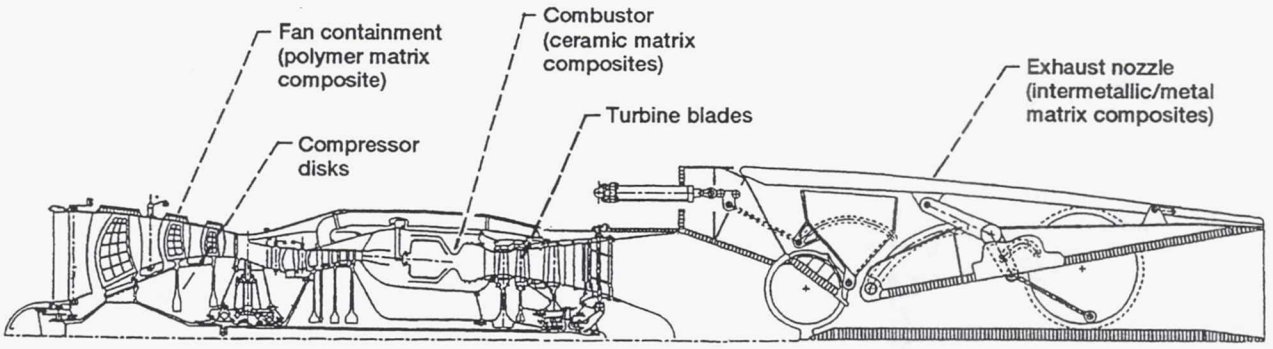

Figure 12.—Advanced materials required for HSCT propulsion system.

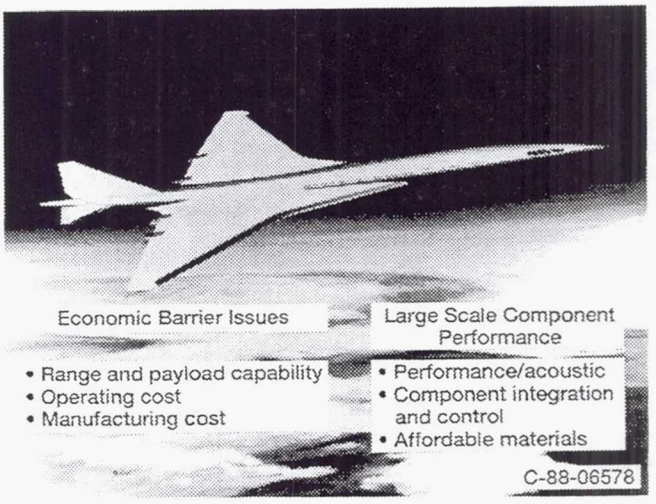

Figure 13.—Economic viability issues — propulsion perspective.

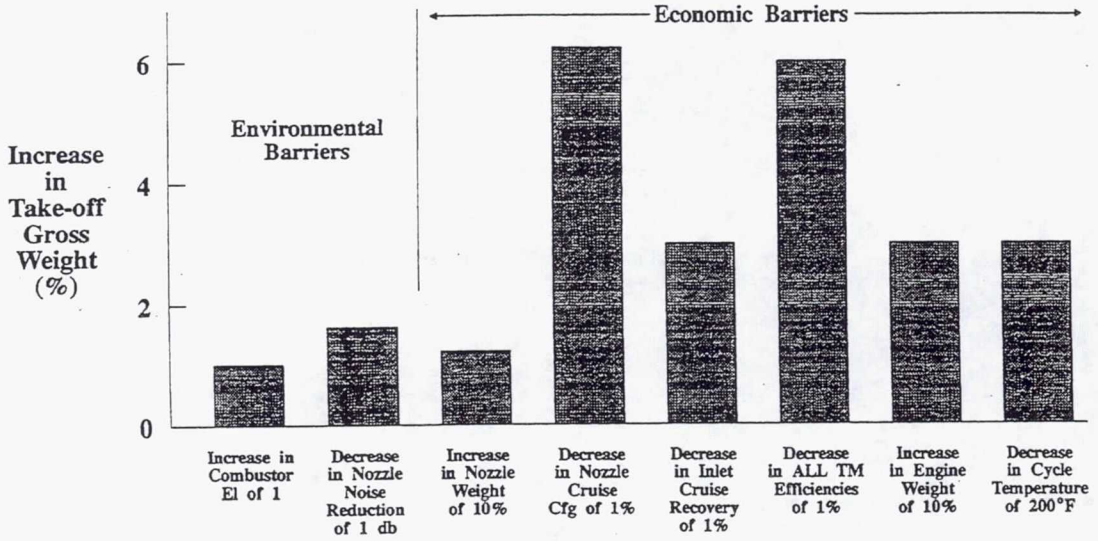

Figure 14.—Impact of propulsion technologies on HSCT viability.

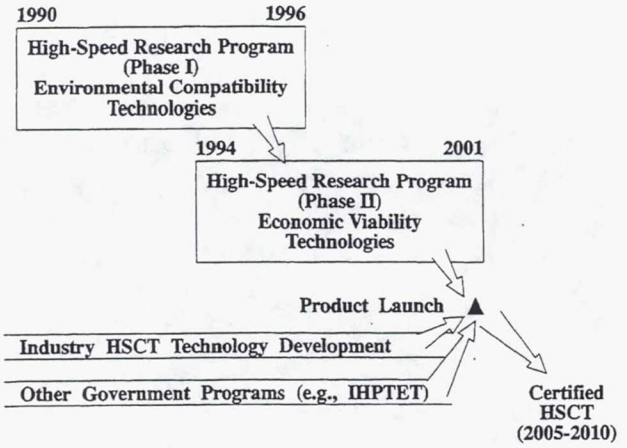

Figure 15.—Possible HSCT scenario.

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13. ABSTRACT ***(Maximum 200 words)***

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